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Research Memorandum
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RADAR BENIGN/NON-BENIGN ENVIRONMENTAL ANALYSIS

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STANFORD RESEARCH INSTITUTE

MENLO PARK, CALIFORNIA

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Prepared for:

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AND
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ABSTRACT

This report describes the major system methodologies pertinent to the evaluation of contemporary fire control systems. It will serve as a useful reference for the systems analyst and as an aid for those who want to supplement their knowledge of the methodologies associated with radar systems analysis. Major emphasis is given to the description of radar performance in a benign and a nonbenign environment. Extensive references are included. This work was undertaken as part of a larger study of radar performance evaluation for the Naval Warfare Research Center of Stanford Research Institute.

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I INTRODUCTION

A. Purpose and Scope

This research memorandum describes some of the major system considerations pertinent to the performance evaluation of contemporary fire control radar systems. Major emphasis is given to the description of radar performance evaluation methodologies in a benign and nonbenign environment. Both qualitative and quantitative appraisals are included throughout to provide an awareness of the minimal system constraints that must be considered in the evaluation of radar systems in various environments. Only the more significant considerations are mentioned, and the references may be consulted for more detailed analysis of the particular type of environment under consideration by the analyst.

B. Organization of the Memorandum

The memorandum has been organized and written to provide the greatest utility for the varied backgrounds of personnel directly or indirectly associated with radar performance evaluation methodology. Section II deals with some of the basic methodologies associated with the evaluation of a radar system in a benign environment. Section III describes some of the basic methodologies associated with the evaluation of a radar system in a nonbenign environment. Section IV presents a methodology for the evaluation of volume clutter for a CW radar. Section V sets forth some of the more pertinent considerations associated with various clutter suppression techniques.

Particular attention is given to the time selectivity clutter suppression techniques, with major emphasis on the analog intermediate frequency (*IF*) double delay line canceller processor. This technique is discussed in detail because it appears to be the optimum for both search and track functions in a benign environment. The methodologies developed in Section V may then be combined with the methodologies developed in Sections II and III to obtain realistic quantitative data pertinent to the evaluation of radar performance in benign and nonbenign environments.

The equations set forth in this memorandum may be readily adapted to perform a comparative analysis of several systems or to assess the expected degradation in a particular system. The equations also illustrate the concepts and system considerations that must be identified during a performance evaluation analysis of a contemporary fire control radar system. The presentation is intentionally brief in the hope that sufficient references and concepts are presented to enable the reader to pursue a more detailed analysis of a specific concept or to extend the basic methodologies to areas that are not included in this memorandum because of time and space constraints.

II RADAR PERFORMANCE IN A BENIGN ENVIRONMENT

A. General

The methodologies associated with the performance evaluation of a radar system in a benign environment are described in this section. In particular, the methodologies associated with (a) clear, (b) ground clutter, (c) sea clutter, and (d) rain models are presented. Other environment models, such as local radar interference, terrain masking, and snow are not presented.

The effects of ground and/or sea clutter and rain are minimal when the radar under evaluation has an operating frequency below *S* band. However, many radars are forced by other considerations to have an operating frequency above *S* band. Some such factors are mobility considerations and the desensitizing of a radar to a standoff jammer (*STOJ*) at the higher frequency. When such considerations force a higher operating frequency, the effects of clutter and rain on the performance of the radar become predominate. For example, the backscattering coefficient of rain varies directly as the fourth power of the operating frequency. Since this backscattered energy from rain contributes to an increase in the radar's receiver noise, the detection range of the radar is decreased accordingly. The backscattered energy at *X* band, as compared to *L* band, is about $(10/1)^4$ times greater. Rain, as well as ground and sea clutter, also has detrimental effects on such system functions as tracking range and tracking accuracy.

Since, with the possible exception of vertical incidence, backscatter by the ground or sea is always diffuse and not a specular reflection, it is often convenient to define a backscattering coefficient of an element of the surface rather than to define a diffuse scattering reflection coefficient for use in an analysis. Such a procedure will be followed in this section. For this purpose an area backscattering coefficient model will be expressed for ground and sea clutter, and a volume backscattering coefficient model will be developed for rain. The radar cross section of the clutter may then be expressed as the product of the area or volume of the clutter and the backscatter coefficient. The signal to clutter ratio

(S/C) may then be expressed in terms of the target to clutter radar cross sections (σ_t/σ_c). After the signal processing gain associated with the radar's receiver, that is, subclutter visibility (*SCV*) has been accounted for, the S/C ratio may be utilized to determine the degradation in radar performance in the presence of clutter.

B. Clear Environment

The *IF* signal to noise ratio (S/N) is determined from the standard radar range equation. This equation is usually expressed as:

$$\frac{S}{N} = \frac{P_t G^2 \lambda^2 \sigma}{(4\pi)^3 k T_0 B \overline{NF}_0 R^4} \tag{1}$$

where

P_t	=	rms transmitted power during the pulse (w)
G	=	antenna power directivity gain
λ	=	transmitted wavelength (m)
σ	=	idealized or effective cross-sectional area of target (m^2)
$\overline{NF}_0$	=	operating noise figure
k	=	Boltzmann's constant = 1.38×10^{-23} (w/Hz/°K)
T_0	=	absolute temperature of noise source—arbitrarily taken as 290°K
B	=	equivalent noise bandwidth of the *IF* amplifier (Hz)
R	=	radar-target range (m).

An alternate and very convenient form of Eq. (1) is the mixed units of length expression,

$$\frac{S}{N} = \frac{P_t G^2 \lambda^2 \sigma}{R^4 B \overline{NF}_0} \tag{2}$$

where R is in nmi, λ is in cm, and σ is in m^2. Reference 1 states that an error of 0.3 dB in S/N will be present when Eq. (2) is used in lieu of Eq. (1).

The idealized radar range equation, that is, the range R_0 at which the *IF S/N* is unity, may likewise be expressed in terms of the mixed units as

$$R_0 = \left(\frac{P_t G^2 \lambda^2 \sigma}{B\overline{NF}_0}\right)^{1/4} \quad . \tag{3}$$

This reference range, R_0, may then be used to arrive at a *S/N* scaling equation of the form

$$\frac{S}{N} = \left(\frac{R_0}{R}\right)^4 \quad . \tag{4}$$

The function of propagation factor, $F^4(R,\lambda,h)$, not shown in Eq. (1), is usually assumed to be unity for most free space propagation. Furthermore, Eq. (1) is valid only in the Fraunhofer region, and an additional loss factor must be introduced into Eq. (1) when the range to the target is less than the quotient of the square of the sum of the antenna and target diameters and the wavelength. In most practical cases the attenuation associated with the near field and Fresnel region may be ignored.

For a coherent pulse doppler radar the ratio of peak signal power to noise power in the output of the matched doppler filter, which corresponds to a specific target range and doppler shift, is given by

$$\frac{S}{N} = \frac{2P_t \tau T_{0t} \lambda^2 \sigma G^2}{(4\pi)^3 T_r k T_0 \overline{NF}\ R^4} F^4(R,\lambda,h) \tag{5}$$

where

P_t = the peak transmitted power (w)

τ = transmitted pulse length (s)

T_r = pulse repetition period (s)

T_{ot} = time on target, time on beam position in scanning radar (s)

h = antenna height

$\overline{NF}$ = receiver noise figure per cycle.

An alternate form of Eq. (5), which is sometimes useful in electronic countermeasures (*ECM*) analysis, incorporates the energy gain product concept. The energy gain product is simply the product of the effective

transmitted energy and the ratio of T_r/T_{ot}. Equation (5), rewritten to account for the energy gain product (EGP), is

$$\frac{S}{N} = \frac{2 \cdot (EGP)}{(4\pi)^3} \frac{T_{o\tau}\lambda^2\sigma G_r}{T_r k T_0 \overline{NF}_0 R^4} F^4(R,\lambda,h) \quad . \tag{6}$$

For an FM/CW radar system the S/N ratio performance may be determined from Eq. (7), where P_{av} is the average transmitted CW power and B is the doppler filer bandwidth. Equation (7) neglects the effects of transmitter modulations.

$$\frac{S}{N} = \frac{P_{av}G^2\lambda^2\sigma}{(4\pi)^3 k T_0 B\overline{NF}_0 R^4} \quad . \tag{7}$$

The idealized range equation [(Eq. (3)] may be rewritten for a pulse doppler system, as in Ref. 2:

$$R_0 = \left[\frac{P_t d_s^2 G^2\lambda^2\sigma}{(4\pi)^3 k T_0 B\overline{NF}_0 dg}\right]^{1/4} \tag{8}$$

where

d_s = signal duty cycle

d_g = gating duty cycle (equal to $1 - d_s$) for an ungated system.

When the performance of a CW radar is compared with the performance of a pulse doppler radar, it should be noted that in a pulse doppler radar only the power in the central spectral line is used for detecting the target. Consequently, to achieve the same useful power return from a target, the peak power for a pulse doppler radar system is related to the average power of a CW system by Eq. (9):

$$P_t = \frac{P_{av(CW)}}{d^2} \tag{9}$$

where d is the duty factor, that is, the ratio of average power to peak power.

C. Ground Clutter

Reference 3 defines clutter in radar as "... the display of a conglomeration of unwanted echoes." The same reference also defines rain return in radar as "clutter due to rain." Clutter echoes may be subdivided into two categories: isolated clutter echoes and composite clutter echoes. The isolated or discrete echo acts as a point scatterer, whereas the composite or distributed echo consists of many individual scatterers. Ground clutter, sea clutter, and rain clutter echoes constitute examples of the latter categorization. Sometimes it is advantageous to classify clutter into area clutter and volume clutter. According to this classification ground and sea clutter are examples of area clutter, and rain clutter is an example of volume clutter.

Backscattering by ground, sea, and rain clutter appears as a diffuse echo to the radar system that is superimposed on other echoes and thus may impair the sensitivity of the receiver. Backscattering usually consists of two components; diffuse scattering and specular reflection. Specular reflection is the type of reflection that is caused by a smooth surface, that is, it is directional and obeys the laws of classical optics. Diffuse scattering, however, has little directivity. Another distinction between the two components is that the fluctuations associated with specular reflections have a relatively small amplitude, whereas the fluctuations associated with diffuse scattering have a large amplitude and, as shown in Ref. 4, are Rayleigh distributed. For ground clutter, if the earth's surface is rough (rough in the Rayleigh sense), then specular reflection is less important than diffuse scattering. Since Rayleigh's criterion of roughness varies inversely as the wavelength, then with the possible exception of vertical incidence, backscatter, at radar frequencies, is always diffuse and not a specular reflection. Reference 5 contains a criterion that may be used to determine when ground reflection is entirely diffuse. This criterion is especially useful for transmission frequencies below, for example, *L* band and when terrain profiles are available for the evaluation.

The amount of backscattering by ground clutter can be defined by a reflection coefficient of diffuse scattering, as is often done in the case of specular reflection. Later in this section a model is described that does utilize the concept of a reflection coefficient of diffuse scattering. However, it appears more convenient to proceed in defining a backscattering radar cross section in a manner analogous to clear environment target

backscattering. To define a backscattering cross section, $d\sigma$, of an element of the earth's surface (assuming area clutter rather than volume clutter), dS, introduce the concept of the cross section per unit of intercepted area (for area clutter), σ^0.

$$\sigma^0 = \frac{d\sigma}{dS} \quad , \tag{10}$$

and thus for area clutter the clutter cross section may be written as*

$$\sigma_c = A_c\sigma^0 = A_i\sigma^0/\sin\theta \tag{11}$$

where A_i is the incident area of the clutter, that is, the area perpendicular to the line of sight (LOS) through which passes all the reflected energy that contributes to clutter echo in pulse radars.

$$A_i = \frac{c\tau}{2}\tan\theta\, R_c\theta_a \tag{12}$$

where

τ = effective pulse width
θ_a = effective azimuth beamwidth
θ = incidence angle
R_c = range to clutter.

In Eq. (12) it is implicitly assumed that the range resolution interval of the radar is in fact $c\tau/2$. If this is not the case, then the equation should be changed to reflect that fact.

The clutter reflectivity factor, σ^0, is dependent on the type of terrain assumed and may or may not be a function of the incidence angle. For dry, rough terrain the clutter reflectivity factor is essentially independent of the incidence angle, whereas for a smooth water surface, the clutter reflectivity factor will vary markedly with incidence angle. Swamp land and choppy water surfaces will lie between these two extremes. It should be noted that in the literature the radar return from clutter is sometimes specified by the parameter γ. Reference 6 defines this parameter as

$$\gamma = \sigma^0/\sin\theta \quad . \tag{13}$$

* For small θ, σ_c is essentially independent of θ.

From Ref. 7, the power received by a pulsed radar may be obtained from

$$P_r = P_t \frac{G^2\lambda^2}{(4\pi)^3 z^2} \int_0^{\frac{\pi}{2}} f^4(\theta)\Phi(\theta)\sigma^0(\theta) p \left(\frac{z}{\sin\theta}\right) d\theta \qquad (14)$$

where

P_t = peak transmitted power

G = antenna directive power gain

z = height of the radar above the surface

θ = grazing angle (at short ranges-radar elevation angle)

$f^2(\theta)G$ = antenna gain in the direction making an angle θ with horizontal

$\Phi(\theta)$ = area of the plane at an inclination θ intercepted by the radar

$p(z/\sin\theta)$ = proportional to the absolute value of the Poynting vector of the incident wave at a distance $r = (z/\sin\theta)$ from the radar.

As is noted in Ref. 7, Eq. (14) simplifies in two cases: when θ is small and when θ is large (near 90°). Equation (15) is for θ small, and Eq. (16) is for θ large.

$$P_r = P_t \frac{G^2\lambda^2}{(4\pi R)^3} f^4(\theta)\Phi \frac{c\tau}{2} \sigma^0(\theta) \qquad (15)$$

$$P_r = P_t \frac{G^2\lambda^2}{(4\pi z)^2} \Theta\Phi \sin\theta\, \sigma^0(\theta) \qquad (16)$$

where Θ is the area of the vertical plane intercepted by the radar beam.

The transition between the two equations occurs at an angle for which the distance on the surface illuminated by the vertical section of the beam is equal to the pulse length on the surface, that is, at an angle θ so that Eq. (17) is valid.

$$\tan\theta = \frac{\theta_e R}{c\tau/2} \qquad (17)$$

The phenomenological Eqs. (14), (15), and (16) require no assumptions about the specific nature of the scatterers.* In Eqs. (15) and (16) the clutter received power (sometimes labeled C) is written as a function of the clutter reflectivity factor. This equation may also be written as a function of the reflection coefficient δ. From Eqs. (9) and (10) of Ref. 8, the intensity of the signal returned from ground clutter may be written as

$$P_r = \frac{P_t \lambda^2 G^2}{(4\pi)^3 R^4} R \Delta\alpha \frac{c\tau}{2} \sec\beta_2 \, F(\beta_2) \tag{18}$$

where

$\Delta\alpha$ = beam width of antenna, measured in a plane containing the LOS

β_2 = angle at the target, measured up from the surface of the ground to the LOS

$F(\beta_2)$ = aspect function.

Reference 9 arrives at an aspect function that "approximates the measured data better" than the best aspect function of Ref. 8. This aspect function is

$$F(\beta_2) = \frac{\delta}{2} \sin 2\beta_2 (\sec \beta_2)^{-1} (1 + \tan \beta_2) \quad . \tag{19}$$

By substituting Eq. (19) into Eq. (18), the received clutter power from ground clutter may be expressed as a function of the reflection coefficient δ, by

$$P_r = \frac{P_t \lambda^2 G^2}{4(4\pi)^3 R^3} \Delta\alpha c\tau \sin 2\beta_2 (1 + \tan \beta_2)\delta \quad . \tag{20a}$$

for small grazing angles

$$P_r = \frac{P_t \lambda^2 G^2}{(4)^4 \pi^2 R^2} \Delta\alpha^2 \cos^2 \beta_2 (1 + \tan \beta_2)\delta \quad . \tag{20b}$$

for large grazing angles

* Equation (16) is valid only for pencil beams and breaks down at high angles for $\csc^2$ beam.

References 10, 11, and 12 are but a small sample of the literature that exists on the determination of the reflection coefficient from ground clutter. For vegetation that is dense and completely covers the ground surface, the reflection coefficient is on the order of 0.1, regardless of the polarization of the incident energy. For less dense vegetation, the ratio of the diffuse to smooth earth reflection coefficient is generally in the region of 0.3 to 0.4. For analysis purposes, if a smooth earth reflection coefficient of, for example, 0.9 is assumed, then for an intermediate surface the reflection coefficient may typically be on the order of 0.3, and for a dense surface it is as always, 0.1. If a more detailed analysis is desired, then the reflection coefficient may be calculated for the smooth earth case from the standard equations in Ref. 13. Then the smooth earth case, under analysis, may be scaled to the intermediate case, and for the rough case (rough in the Rayleigh sense), the reflection coefficient of 0.1 is assumed to predominate.

For degradation analysis of a radar system's performance in the presence of ground clutter, it is often convenient to perform the analysis by using the signal to clutter ratio, S/C, rather than to calculate the magnitude of the received clutter power by using such equations as (15), (16) or (20). By determining the S/C ratio, the analysis may be made sensitive to the signal processing techniques of the radar's receiver. This is done by determining the subclutter visibility of the receiving circuits and increasing the S/C ratio by the corresponding amount. Then if the S/C ratio exceeds some specified value needed for detection, it is assured that detection will occur under the assumed circumstances and geometry. Thus this latter methodology is effective if the radar's performance in a clutter environment is considered, or when detection is used as a measure of the radar's performance. From taking the S/N ratio equation for a target in the clear and the C/N ratio equation for a clutter target, then it is seen that

$$S/C = (\sigma_t/\sigma_c)(R_c/R_t)^4(G_{rt}/G_{rc})^2 \qquad (21)$$

where

σ_t = target cross section of target to be detected

σ_c = clutter cross section

R_c = range to the clutter

R_t = range to the target

G_{rt} = antenna power gain in direction of target

G_{rc} = antenna power gain in direction of clutter.

Assuming that the antenna gain for the target and clutter are the same and assuming that the range to the target and clutter are the same, then Eq. (21) may be written as

$$S/C = (\sigma_t/\sigma_c) \quad . \tag{22}$$

For ground clutter (area clutter), the clutter cross section may be expressed as the product of the area of the clutter illuminated and the clutter reflectivity factor, namely,

$$S/C = \sigma_t/(A_c\sigma^0) \quad . \tag{23}$$

For a pulse radar Eq. (11) may be used to calculate the area clutter with the implicit assumption stated in its derivation. From Ref. 14, Eq. (24) may be used for a *CW* radar.

$$A_c = \frac{\pi\theta_a\theta_e R_c^2}{4 \sin E} \tag{24}$$

where E is the radar elevation angle.

The value of the clutter reflectivity that is to be used in Eq. (23) depends on the type of analysis to be conducted. From Ref. 15, the clutter reflectivity may be expressed solely as a function of the radar transmitting frequency,*

$$\sigma^0 = 1.9 \times 10^{-15} f^{1.333} \quad . \tag{25}$$

In other instances, tabular values of the clutter reflectivity may be determined by consulting the vast literature on the determination of this parameter. For rapid analysis, values of about -20 dB may be assumed for the clutter reflectivity factor. Substituting Eq. (11) and Eq. (25) into Eq. (23), then the S/C ratio may be expressed as

$$\frac{S}{C} = \frac{2\sigma_t}{1.9 \times 10^{-15} c\tau \sec\theta\, R_c\theta_a f^{1.333}} \quad . \tag{26}$$

---

* For rapid calculation σ^0 may be approximated by $\sigma^0 = (0.0003\lambda)$.

Reference 16 has shown that the clutter reflectivity increases with frequency, as noted in Eq. (25). This form of the clutter reflectivity may be preferred since various experiments will arrive at different values for the clutter reflectivity. For example, in the previously cited Ref. 15 the clutter reflectivity at 3 cm varies from -15 to -30 dB from one experiment to another. Thus Eq. (26) will be used for determining the *S/C* of a system. Reference 6 may be consulted for the theoretical expressions for calculating the radar cross section of ground clutter or the method in Refs. 8 and 9 may be also used when the reflection coefficient and geometry are significant:

$$\sigma^0 = \frac{\delta}{2} \sin 2\beta_2 \frac{(1 + \tan \beta_2)}{\sec \beta_2} \quad . \tag{27}$$

D. <u>Sea Clutter</u>

Sea clutter, in general, is not so severe in degrading the detection performance of a radar system. However, diffuse scattering predominates when the sea is rough, and there are large and rapid fluctuations in the reflected signal from the surface of the sea. In this instance sea clutter may seriously degrade the performance of a radar, especially for the detection of targets near the surface of the sea. A detailed analysis of sea clutter is more complex than an analysis of ground clutter. One reason for this additional complexity is that the clutter reflectivity factor will have a frequency dependency of f^4 for Sea State 1 and a frequency dependency of f^0, *i.e.*, independent for a Sea State 6. For comparative analysis it is customary to use an f^2 dependency that is valid for a moderate to rough sea state, Sea State 3 to Sea State 4. References 17 through 20 may be consulted for more detailed description of the theoretical studies and experimental investigations of the surface of the sea.

From Ref. 21 the value of the clutter reflectivity for sea clutter may be calculated from*

$$\sigma^0 \doteq 9 \times 10^{-3} \lambda^{-1} W^{3/4} (1 \pm 2 \times 10^{-3} W) N_0 \tag{28}$$

where

N_0 = an experimental constant (7.2×10^{-5})

W = windspeed (knots)

$\pm$ = + for upwind and - for downwind .

*For grazing incidents and small facets.

If the model for σ^0 in Eq. (28) is used in the S/C equation, it should be noted that the model is very limited because the derivation of Eq. (28) is based on many simplifying assumptions. (Note the f^1 dependency of the model.) If a more detailed model is needed, then the references should be consulted for the dependency of the clutter reflectivity on such parameters as the grazing angle, sea state, polarization, etc.

For a smooth sea surface, Ref. 22 has the following model

$$\sigma^0 = \frac{13.1 \times 10^3}{\psi^2} \exp\left[-(10^4/\psi^2)(\theta - \pi/2)^2\right] \tag{29}$$

where

ψ = half-power antenna beamwidth in degrees

θ = radar grazing angle in radians .

For a rough sea surface Ref. 22 proposes the following model

$$\sigma^0 = 2 \sin \theta \quad . \tag{30}$$

Caution is necessary in using Eq. (30) because the values received for extremely small angles will be about twice as great as the values determined in various experiments. In other words at a grazing angle of, for example, 6 minutes, the calculated clutter reflectivity would be about -25 dB, whereas the actual value may tend to be closer to -50 dB. Reference 23 contains several graphs of the clutter reflectivity as a function of the polarization and depression angle of the radar. For rapid analysis a clutter reflectivity factor of -50 dB may be used at L band and -40 dB at X band. If a closed form for the grazing angle dependency of the clutter reflectivity is desired, then one such form from Ref. 24, is

$$\sigma^0 = K_0 \exp\left(-K_3\theta^{K_4}\right) \doteq 10 \exp\left(-0.5\theta^{0.7}\right) \quad . \tag{31}$$

The reader is referred to Ref. 25 for a synoptic discussion on the radar reflectivity of the earth's surface. Figure 6 of that reference is reproduced here in Fig. 1 as a synopsis of the discussion on clutter reflectivity for ground and sea clutter.

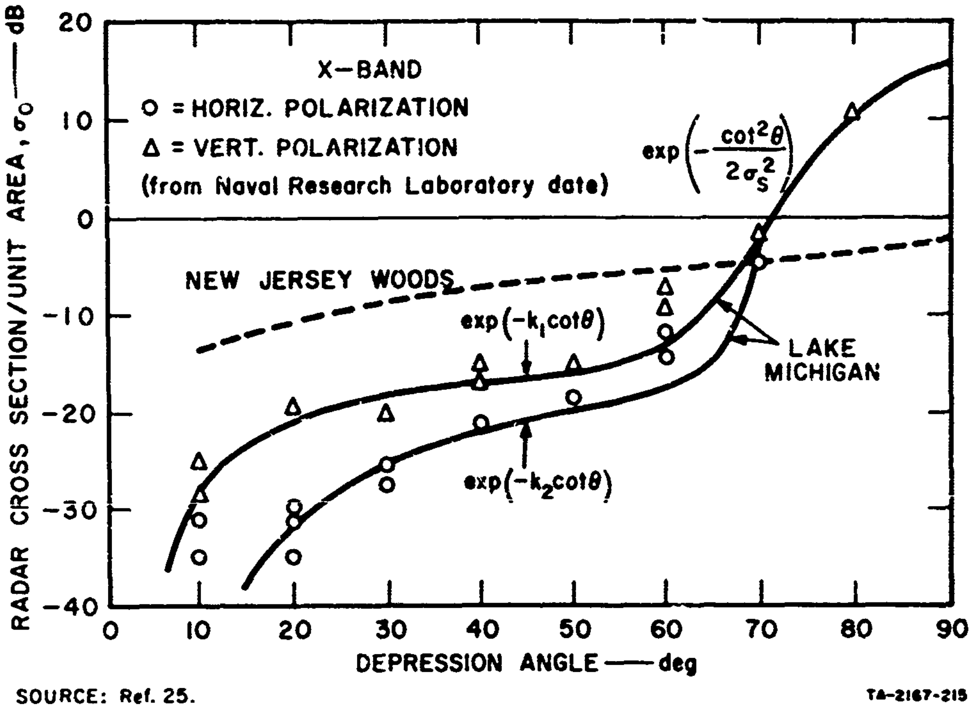

FIG. 1 VARIATION OF THE RADAR CROSS SECTION OF A ROUGH SURFACE WITH DEPRESSION ANGLE, IN WATER-COVERED AND FOREST-COVERED SURFACES

E. Rain Clutter

As is stated above in part C rain radar returns form a subgroup of radar clutter. Rain clutter is a subclass of volume clutter, whereas ground and sea clutter are subclasses of area clutter. From Ref. 7, the phenomenological equation for the average received power for meteorological volume clutter (clutter that fills a volume around a target) is

$$P_r = \frac{P_t G^2 \lambda^2 \theta \Phi c \tau \eta}{2(4\pi)^3 R^2} \tag{32}$$

where

θ and Φ = the horizontal and vertical beamwidths, in general

η = radar cross section of the volume clutter per unit volume.

The volume illuminated by the beam $[(1/2)\theta\Phi c\tau]$ is sometimes written as

$$V_c = (\pi/8)\theta_a \theta_e c\tau R_c^2 \tag{33}$$

where

$(\pi\theta_a\theta_e)/4$ = solid angle within the radar beam

$c\tau/2$ = assumed to be the effective range resolution.

Radar detection performance in rain is degraded owing to the backscattering from the water particles and the attenuation of the signal due to precipitation. Equation (32) was derived on the assumption that the backscattering from the water particles is incoherent, and as such this backscattering noise may be added directly to the receiver noise in the radar range equation. However, caution must be exercised by the analyst when utilizing such a methodology since, in reality, the backscatter noise will appear coherent to an integration process within the signal processing networks of the radar receiver. Thus, although radar integration techniques will usually improve the S/N_r ratio, where N_r is the receiver noise, it will not necessarily improve the S/N_c ratio, where N_c is the clutter noise due to the backscattering from the water particles. For the calculation of the S/C ratio for volume clutter, Eq. (23) may be written as

$$S/C = \sigma_t/(V_c\eta) \quad . \tag{34}$$

From Ref 26, the correction factor that accounts for the attenuation over the path of the beam may be expressed as a function of R in wet weather

$$\psi = \exp - 0.461R_w(H\beta + \alpha, \tag{35}$$

where the terms of the exponent are defined as follows

H = absolute humidity (g/m^3)

β = one-way water-vapor attenuation factor per unit of absolute humidity (dB/meter/g/m^3)

α = one-way attenuation due to scattering (dB/m).

If the one-way attenuation due to rain is known, then Eq. (36) may be used to calculate the attenuation loss (L_a) due to rain

$$L_a = 10^{0.2L_rR_t} \tag{36}$$

where

L_r = one-way attenuation due to rain (dB/m)

R_c = range amount of rain that signal transverses (m).

From Ref. 27, Tables I and II may be referred to for modeling values of L_r.

The effective radar cross section of the backscattered part of the rain that reaches the radar receiver simultaneously with the target signal is sometimes written as the product of the volume of the clutter and of one of the symbols η, σ_u, or σ^0. Since it is customary to define σ^0 as the backscatter cross section per unit area and it is common practice to use a σ subscripted as the cross section of a target, then the symbol η will be used in this memorandum to designate the backscattered cross section per unit volume (m^2/m^3). Sometimes the scattering coefficient is given in terms of per unit solid angle. For example, from Ref. 28

$$\sigma = 4.6 \times 10^{-15} R^{1.6} \lambda^{-4} \qquad (37)$$

where

R = rainfall rate (mm/hour)

λ = transmitted wavelength (m).

Note that the scattering coefficient varies directly as f^4, so that the lower frequency radars will have less degradation due to rain than the higher frequency radars.

Reference 29 has tabulated the values for η in terms of the number of drops per unit volume and the scattering function of the drop. This reference should be consulted when a fine-grain analysis of a system is to be conducted. However, the 5 to 50 at 5 rule, given below, is usually valid for most analyses and will be used here. This rule basically states that for light (5) or moderate rain (50), at C band (5), the rain reflectivity for light rain (1 mm/hr) is about 5 m^2/km^3 and for moderate rain (4 mm/hr) is about 50 m^2/km^3. Thus, for example, at 1000 MHz, the equivalent rain clutter reflectivity would be about $(5)(1/5)^4 = 0.008\ m^2/km^3$ for light rain. For moderate rain, at 10,000 MHz, the rain reflectivity would be about $(50)(10/5)^4 = 800\ m^2/km^3$.

Table I

ATTENUATION IN DB/KM DUE TO PRECIPITATION AT THE RATE OF 1 MM/HOUR, COMPOSED OF DROPS OF EQUAL DIAMETER *D* (TEMPERATURE 20°C)

DROP DIAMETER (cm)	WAVELENGTH (cm)															
	0.3	0.5	1	1.5	2	3	4	5	5.5	6	6.5	7	8	9	10	15
0.05	1.85	0.46	0.97×10^{-1}	0.43×10^{-1}	0.19×10^{-1}	0.75×10^{-2}	0.34×10^{-2}	0.24×10^{-2}	0.13×10^{-2}	0.10×10^{-2}	0.85×10^{-3}	0.71×10^{-3}	0.54×10^{-3}	0.45×10^{-3}	0.40×10^{-3}	0.25×10^{-3}
0.10	1.49	0.74	0.14	0.48×10^{-1}	0.18×10^{-1}	0.59×10^{-2}	0.28×10^{-2}	0.15×10^{-2}	0.12×10^{-2}	0.94×10^{-3}	0.76×10^{-3}	0.63×10^{-3}	0.46×10^{-3}	0.36×10^{-3}	0.29×10^{-3}	0.13×10^{-3}
0.15	0.66	0.68	0.20	0.77×10^{-1}	0.34×10^{-1}	0.72×10^{-2}	0.28×10^{-2}	0.15×10^{-2}	0.12×10^{-2}	0.93×10^{-3}	0.74×10^{-3}	0.61×10^{-3}	0.43×10^{-3}	0.32×10^{-3}	0.25×10^{-3}	0.10×10^{-3}
0.20	0.41	0.42	0.22	0.12	0.63×10^{-1}	0.13×10^{-1}	0.40×10^{-2}	0.18×10^{-2}	0.13×10^{-2}	0.10×10^{-2}	0.80×10^{-3}	0.64×10^{-3}	0.42×10^{-3}	0.30×10^{-3}	0.23×10^{-3}	0.91×10^{-4}
0.25	0.28	0.28	0.22	0.11	0.88×10^{-1}	0.24×10^{-1}	0.60×10^{-2}	0.23×10^{-2}	0.16×10^{-2}	0.12×10^{-2}	0.91×10^{-3}	0.73×10^{-3}	0.47×10^{-3}	0.31×10^{-3}	0.24×10^{-3}	0.86×10^{-4}
0.30	0.21	0.21	0.21	0.11	0.74×10^{-1}	0.44×10^{-1}	0.98×10^{-2}	0.34×10^{-2}	0.23×10^{-2}	0.15×10^{-2}	0.11×10^{-2}	0.89×10^{-3}	0.55×10^{-3}	0.36×10^{-3}	0.27×10^{-3}	0.87×10^{-4}
0.35	0.17	0.17	0.18	0.11	0.71×10^{-1}	0.67×10^{-1}	0.19×10^{-1}	0.51×10^{-2}	0.32×10^{-2}	0.21×10^{-2}	0.15×10^{-2}	0.11×10^{-2}	0.67×10^{-3}	0.43×10^{-3}	0.31×10^{-3}	0.91×10^{-4}
0.40	0.14	0.14	0.15	0.11	0.71×10^{-1}	0.49×10^{-1}	0.35×10^{-1}	0.83×10^{-2}	0.47×10^{-2}	0.30×10^{-2}	0.21×10^{-2}	0.15×10^{-2}	0.84×10^{-3}	0.53×10^{-3}	0.36×10^{-3}	0.99×10^{-4}
0.45	0.12	0.12	0.12	0.12	0.72×10^{-1}	0.41×10^{-1}	0.57×10^{-1}	0.16×10^{-1}	0.87×10^{-2}	0.47×10^{-2}	0.30×10^{-2}	0.20×10^{-2}	0.11×10^{-2}	0.66×10^{-3}	0.43×10^{-3}	0.11×10^{-3}
0.50	0.10	0.11	0.11	0.11	0.75×10^{-1}	0.40×10^{-1}	0.44×10^{-1}	0.32×10^{-1}	0.16×10^{-1}	0.78×10^{-2}	0.46×10^{-2}	0.29×10^{-2}	0.15×10^{-2}	0.83×10^{-3}	0.53×10^{-3}	0.12×10^{-3}
0.55	0.92×10^{-1}	0.96×10^{-1}	0.99×10^{-1}	0.97×10^{-1}	0.78×10^{-1}	0.41×10^{-1}	0.34×10^{-1}	0.51×10^{-1}	0.26×10^{-1}	0.41×10^{-1}	0.81×10^{-2}	0.44×10^{-2}	0.20×10^{-2}	0.11×10^{-2}	0.67×10^{-3}	0.14×10^{-3}
0.60	0.83×10^{-1}	0.87×10^{-1}	0.91×10^{-1}	0.88×10^{-1}	0.83×10^{-1}	0.42×10^{-1}	0.29×10^{-1}	0.48×10^{-1}	0.47×10^{-1}	0.23×10^{-1}	0.14×10^{-1}	0.81×10^{2}	0.28×10^{-2}	0.14×10^{-2}	0.87×10^{-3}	0.16×10^{-3}
0.65	0.76×10^{-1}	0.79×10^{-1}	0.83×10^{-1}	0.82×10^{-1}	0.95×10^{-1}	0.46×10^{-1}	0.28×10^{-1}	0.30×10^{-1}	0.45×10^{-1}	0.41×10^{-1}	0.22×10^{-1}	0.14×10^{-1}	0.42×10^{-2}	0.19×10^{-2}	0.11×10^{-2}	0.19×10^{-3}
0.70	0.70×10^{-1}	0.73×10^{-1}	0.77×10^{-1}	0.77×10^{-1}	0.77×10^{-1}	0.51×10^{-1}	0.27×10^{-1}	0.23×10^{-1}	0.30×10^{-1}	0.48×10^{-1}	0.41×10^{-1}	0.21×10^{-1}	0.68×10^{-2}	0.26×10^{-2}	0.14×10^{-2}	0.22×10^{-3}
MAXIMUM ATTENUATION	2.37	0.76	0.22	0.12	0.95×10^{-1}	0.68×10^{-1}	0.58×10^{-1}	0.53×10^{-1}	0.54×10^{-1}	0.53×10^{-1}	0.22×10^{-1}	0.14×10^{-1}	0.42×10^{-2}	0.19×10^{-2}	0.11×10^{-2}	0.25×10^{-3}
MINIMUM ATTENUATION	0.76×10^{-1}	0.79×10^{-1}	0.83×10^{-1}	0.40×10^{-1}	0.17×10^{-1}	0.59×10^{-2}	0.27×10^{-2}	0.15×10^{-2}	0.12×10^{-2}	0.93×10^{-3}	0.74×10^{-3}	0.61×10^{-3}	0.40×10^{-3}	0.30×10^{-3}	0.23×10^{-3}	0.86×10^{-4}

SOURCE: Ref. 27.

Table II

ATTENUATION IN DB/KM FOR VARIOUS RATES OF PRECIPITATION ASSUMING THE LAWS AND PARSONS' DROP-SIZE DISTRIBUTION (TEMPERATURE 20°C)

PRECIPITATION RATE (mm/hour)	WAVELENGTH (cm)															
	0.3	0.5	1	1.5	2	3	4	5	5.5	6	6.5	7	8	9	10	15
0.25	0.230	0.159	0.349×10^{-1}	0.136×10^{-1}	0.572×10^{-2}	0.172×10^{-2}	0.757×10^{-3}	0.442×10^{-3}	0.309×10^{-3}	0.242×10^{-3}	0.196×10^{-3}	0.162×10^{-3}	0.119×10^{-3}	0.939×10^{-4}	0.780×10^{-4}	0.396×10^{-4}
1.25	1.29	0.764	0.210	0.878×10^{-1}	0.423×10^{-1}	0.116×10^{-1}	0.431×10^{-2}	0.218×10^{-2}	0.160×10^{-2}	0.123×10^{-2}	0.986×10^{-3}	0.809×10^{-2}	0.572×10^{-3}	0.434×10^{-3}	0.350×10^{-3}	0.159×10^{-3}
2.5	2.19	1.43	0.447	0.196	0.100	0.284×10^{-1}	0.101×10^{-1}	0.465×10^{-2}	0.339×10^{-2}	0.257×10^{-2}	0.203×10^{-2}	0.165×10^{-2}	0.112×10^{-2}	0.851×10^{-3}	0.678×10^{-3}	0.294×10^{-3}
5	3.68	2.63	0.933	0.427	0.233	0.718×10^{-1}	0.252×10^{-1}	0.107×10^{-1}	0.749×10^{-2}	0.554×10^{-2}	0.430×10^{-2}	0.346×10^{-2}	0.234×10^{-2}	0.170×10^{-2}	0.133×10^{-2}	0.550×10^{-2}
12.5	7.08	5.46	2.43	1.18	0.709	0.240	0.848×10^{-1}	0.336×10^{-1}	0.226×10^{-1}	0.159×10^{-1}	0.120×10^{-1}	0.941×10^{-2}	0.586×10^{-2}	0.429×10^{-2}	0.330×10^{-2}	0.128×10^{-2}
25	11.7	9.86	4.87	2.49	1.53	0.602	0.223	0.882×10^{-1}	0.580×10^{-1}	0.383×10^{-1}	0.279×10^{-1}	0.213×10^{-1}	0.127×10^{-1}	0.900×10^{-2}	0.678×10^{-2}	0.247×10^{-2}
50	19.6	17.0	9.59	5.15	3.28	1.45	0.590	0.235	0.152	0.971×10^{-1}	0.678×10^{-1}	0.499×10^{-1}	0.283×10^{-1}	0.194×10^{-1}	0.142×10^{-1}	0.489×10^{-2}
100	33.7	29.4	18.4	10.4	6.77	3.43	1.55	0.639	0.416	0.260	0.174	0.123	0.659×10^{-1}	0.432×10^{-1}	0.309×10^{-1}	0.989×10^{-2}
150	46.8	40.9	26.8	15.7	10.2	5.49	2.71	1.13	0.739	0.472	0.313	0.214	0.110	0.700×10^{-1}	0.492×10^{-1}	0.151×10^{-1}

SOURCE: Ref. 27.

Reference 30 contains basic methodologies for calculating η for other forms of weather clutter, for example, clouds and snow aggregates. By using the values given in Table 4.1 of Ref. 30, η for rain (moderate) may be written as

$$\eta = 5.7 \times 10^{-14} R^{1.6} \lambda^{-4} \tag{38}$$

where the wavelength is in meters and the rainfall rate is in mm/hour. Figure 2, which is Fig. 12.10 of Ref. 31, graphically shows η in cm^2/m^3 as a function of the rainfall rate and the wavelength. From Ref. 2, Fig. 3 illustrates the variation of the signal attenuation as a function of the wavelength and the rainfall rate. Figures 2 and 3 may be used collectively to determine the upper and lower bounds for a sensitivity analysis. Such a procedure would allow L_r in Eq. (36) to be set for a particular analysis and η may be selected directly from Fig. 2, without resorting to one of the analytical models.

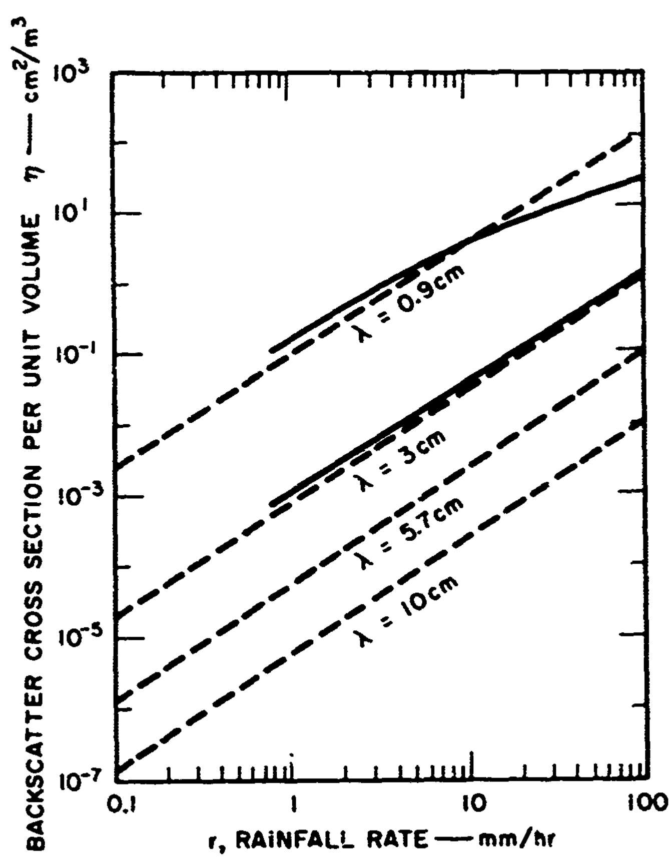

FIG. 2 EXACT (Solid Curves) AND APPROXIMATE (Dashed Curves) BACKSCATTERING CROSS SECTION PER UNIT VOLUME OF RAIN AT A TEMPERATURE OF 18°C

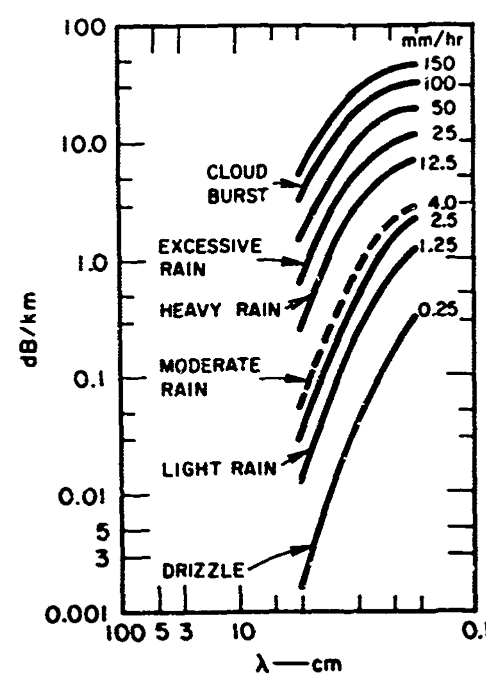

FIG. 3 THE VARIATION OF ATTENUATION WITH WAVELENGTH FOR VARIOUS RAINFALL RATES

If desired the attenuation factors for various fog visibilities and various rainfall rates may be read directly from Figs. 4 and 5, which are taken from Ref. 26. From the same reference Figs. 6 and 7 illustrate the reduction in range capability for several rainfall rates and reduction by attenuation and backscattering.

F. Summary

This section has introduced some of the basic methodologies associated with the performance evaluation of a radar system in a benign environment. The benign environment is one constraint on the low altitude performance of a radar system.

Two basic methods may be used in evaluating the performance of a system in the presence of ground clutter: calculation of the clutter power received from the clutter source or determination of the signal-to-clutter ratio for the system. The signal-to-clutter ratio affords several advantages to modeling and rapid analysis. Since the signal-to-clutter ratio may be simply expressed as a function of the target cross section, the clutter area, and the backscattering coefficient, rapid calculations utilizing several models of the backscattering coefficient set forth in this section are possible.

It was noted that ground clutter is more severe than sea clutter, but is less complex. At vertical incidence the backscatter coefficient is inversely proportional to the wind speed in contrast to the direct proportionality to wind speed at small depression angles, as evident by the model of Eq. (28).

The only benign volume clutter discussed was that of rain. It will be seen in Section V that rain clutter may be a very serious form of degradation to a *CW* radar even in the presence of high subclutter visibility.

If a fine-grain analysis needs to be conducted on the performance evaluation of a radar in a benign environment, then the radar returns should be subdivided into two components, a specular component and a scattered component, the former a reflection from a smooth surface and the latter a scattering from a rough surface. These two components may then be combined and a clutter-to-noise ratio may be used as a measure of the degradation that may be expected in a benign environment.

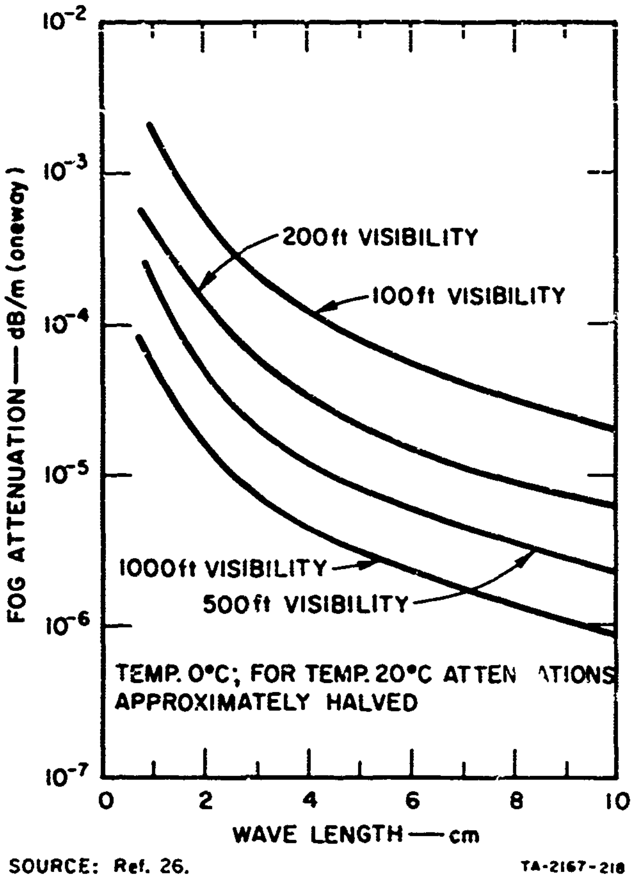

FIG. 4 ATTENUATION FACTORS FOR VARIOUS FOG VISIBILITIES

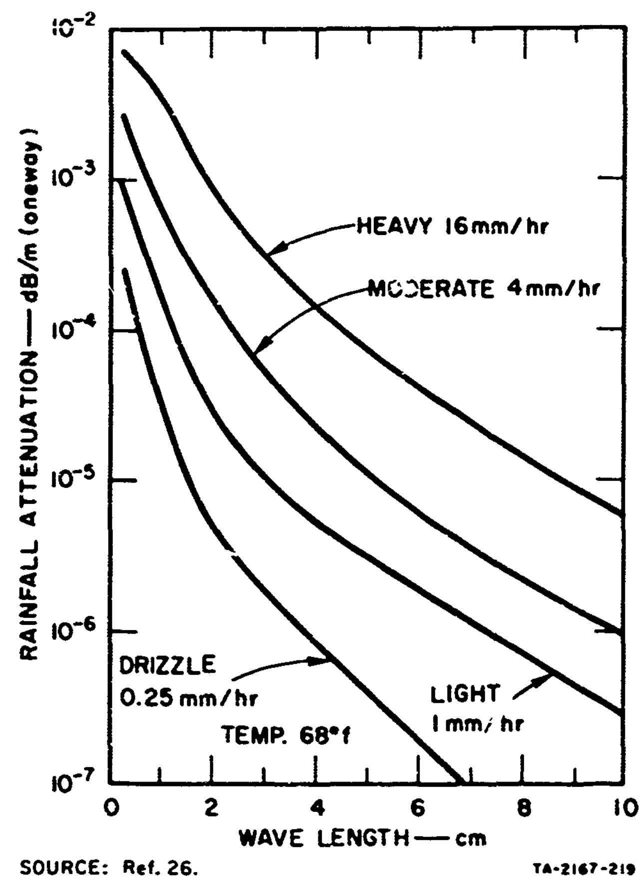

FIG. 5 ATTENUATION FACTORS FOR VARIOUS RAINFALL RATES

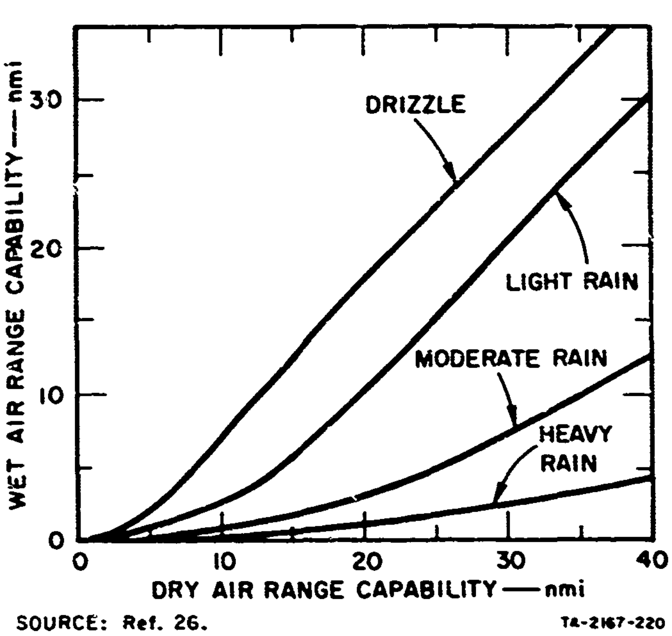

FIG. 6 REDUCTION IN RANGE CAPABILITY FOR SEVERAL RAINFALL RATES
(X-band Radar)

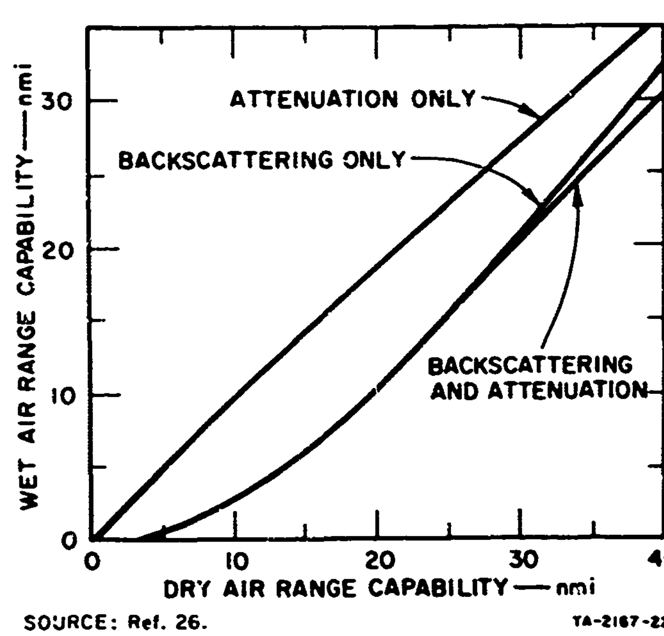

FIG. 7 COMPARATIVE REDUCTION IN RANGE CAPABILITY IN LIGHT RAIN CAUSED BY ATTENUATION AND BACKSCATTERING
(X-band Radar)

Although area and volume clutter were considered, discrete clutter may be very severe for a radar, especially if the range to the discrete clutter source is less than 25 miles.

It is hoped that the reader has gained some additional insight into some of the basic considerations that must be evaluated for a radar system that is operating in a benign environment. Sufficient references have been included so that the reader may expand his knowledge in any area of immediate concern.

III RADAR PERFORMANCE IN A NON-BENIGN ENVIRONMENT

A. General

The methodologies associated with the performance evaluation of a radar system in a non-benign environment are described in this section. In particular, the methodologies associated with (a) chaff, (b) self-screening jammer, (c) standoff jammer and (d) trailing jammer are presented. Other confusion environmental models, such as multiple target generators and decoys, and deception environmental models, such as repeater jammers, inverse gain and gate stealers, are not presented.

It is assumed that the defensive radars' basic electronic counter countermeasure (*ECCM*) strategy is to force a jammer to optimize his tactics around such confusion techniques as active, wide band and narrow band noise jammers. Consequently it is assumed that the defensive radars will incorporate the required minimum number of antijamming (*aj*) fixes that will counter any special or deceptive jamming techniques that may be encountered.

The efficiency of various types of jamming signals is usually measured in terms of the jam-to-signal (J/S) ratio. For such jamming techniques as amplitude and frequency modulated jamming, J/S is the ratio of the rms of the unmodulated carrier power of the jammer to the rms of the radar output multiplied by the inverse of the duty cycle. In the case of direct noise amplification (*DINA*) noise (noncolored), J/S is the ratio of the rms of the noise to the peak power of the pulse.

To compute the J/S ratio for a given radar the basic methodology is (a) calculate the number of pulses per scan for the radar (which is a function of the beamwidth, pulse repetition frequency and scan rate), then (b) determine the integration loss due to noncoherent integration of the number of hits determined in (a). The S/N gain over a single pulse (in dB) is then (c) calculated by subtracting (b) from (a). The value (in dB) calculated in (c) is then subtracted from the S/N ratio for coherently integrated pulses (usually assumed to be about 5.5 dB). The value calculated is then inverted to form the required J/S ratio.

The above brief description illustrates some of the basic considerations that must be accounted for in an analysis of the efficiency of the jammer. Usually, for comparative analysis of systems in an active confusion nonbenign environment, a value of J/S greater than, for example, -13 dB is needed to degrade a systems performance. Consequently in the equations set forth in the following sections it may be assumed that the radar must have at least a 13 S/J ratio to ensure detection.

B. Chaff

In conducting a jamming susceptibility analysis of a radar system it necessary to know quantitatively how much the performance of the system degraded by window and other types of jamming signals that are expected to be encountered.

Various types of window are usually divided into two classes: tuned and untuned window. Chaff and tuned rope are examples of the former, and rope and corner reflectors are examples of the latter. Numerous references exist on the elementary theory of chaff, such as Ref. 32, and the pertinent constraints necessary to prevent such phenomenon as birdnesting are well documented. Since chaff is considered a subclass of clutter, that is, of volume clutter, the methodology outlined in Section II of this memorandum is applicable.

Reference 33 states that the overall radar cross section of a chaff cloud of N particles may be approximated by

$$\sigma = 0.18\ \lambda^2 N \quad . \qquad (39)$$

If the particles are a half a wavelength long, 0.01 inch wide, and cut from aluminum foil that is 0.001 inch thick, then the cross section in square feet is

$$\sigma = 30{,}000\ \frac{W}{f_{\mathrm{kMHz}}} \qquad (40)$$

where W is the total chaff weight in pounds and f is the radar frequency in kMHz.

To use the methodology outlined in Section II, E, the radar cross section of the volume clutter per unit volume, η, is set equal to the chaff density. It should be noted that although volume clutter, such as rain, has a radar reflectivity that varies directly with the fourth power of frequency, chaff radar reflectivity usually varies inversely with the

first power of frequency. An approximate relationship that may be used for comparative purposes is

$$\eta = 10 f^{-1} \quad . \tag{41}$$

Therefore, for chaff, the S/C ratio may be expressed as

$$S/C = \frac{\sigma_t}{V_c \eta} = \frac{\sigma_t f}{10 V_c} \quad . \tag{42}$$

C. Self-Screening Jammer

The screening range achieved by a given jammer that is accompanying the target or that is on board the target aircraft is a function of several jammer and radar parameters. The range may be determined by combining the radar two-way equation with the one-way jammer equation and assuming that the jamming noise adds directly to the receiver noise power and is much greater than the receiver noise power.

The two-way radar equation is

$$S = \frac{P_{tr} G_{tr} G_{rr} \lambda^2 \sigma}{(4\pi)^3 R_s^4} \quad , \tag{43}$$

and the one-way jammer equation is

$$J = \frac{P_J G_J \; G_{rr} \lambda^2 B_R}{B_J \quad (4\pi R_J)^2} \quad . \tag{44}$$

Therefore the S/J ratio is

$$\frac{S}{J} = \frac{P_{tr} G_{tr} \sigma R_J^2}{4\pi \dfrac{P_J G_J}{B_J} B_r R_S^4} \tag{45}$$

which, when solved for the screening range in nmi is

$$R_S^4 = \frac{P_{tr} G_{tr} \sigma R_J^2}{4\pi P_J G_J \left(\dfrac{B_r}{B_J}\right)(S/J)} \doteq \frac{2.3 \times 10^{-6} P_{tr} G_{tr} \sigma R_J^2}{P_J G_J \left(\dfrac{B_r}{B_J}\right)(S/J)} \quad . \tag{46}$$

Where

P_{tr} = peak radar transmitter power

G_{tr} = radar transmitter antenna gain

B_r = radar receiver bandwidth (MHz)

P_J = average power transmitted by jammer

G_J = jammer antenna gain

B_J = jammer signal bandwidth (MHz)

S/J = ratio of signal power to jammer power at the radar antenna terminals

R_J = range from the radar to jamming aircraft in nmi.

For an accompanying jammer, or jammer on board the target aircraft, (*SSJ*), Eq. (46) reduces to

$$\frac{R_S^4}{R_J^2} = R_S^2 = \frac{2.3 \times 10^{-8} P_{tr} G_{tr} \sigma}{P_J G_J \left(\frac{B_r}{B_J}\right) (S/J)} \quad . \tag{47}$$

A more convenient form of Eq. (47) for the evaluation of several systems may be determined by assuming that the radar receiver bandwidth is matched to the radar pulse width. Then Eq. (47) may be written as

$$R_S \doteq \left[\frac{2.3 \times 10^{-8} P_{tr} G_{tr} \tau}{S/J}\right]^{1/2} \left[\frac{\sigma}{\frac{P_J G_J}{B_J}}\right]^{1/2} \quad . \tag{48}$$

Note that in Eq. (48), if a jammer has a density of 1 W/MHz and the target cross section is 1 m^2, then Eq. 48 may be written as

$$R_S = \alpha \left[\frac{\sigma}{\frac{P_J G_J}{B_J}}\right]^{1/2} = \alpha \quad . \tag{49}$$

After the constant is evaluated in Eq. (49) for a particular system, it may be substituted in Eq. (48), and Eq. (48) may then be used for

scaling several cases under varying cross sections and jamming power densities. Furthermore it is to be noted from Eq. (49) that if the detection range of the radar is to be increased, then the energy gain product of the radar must be increased accordingly (assuming receiver processing circuitry requires the same S/J ratio for detection). Therefore a measure of the effectiveness of several radars against a specified threat may be in the evaluation of their energy gain product $P_{tr}G_{tr}\tau$.

For a coherent pulse doppler radar, in which a constant false alarm rate (CFAR) detector is employed and a detection threshold of, say, 16 dB is needed, the required effective radiated jammer noise po... density may be found from Eq. (6), as

$$\left(\frac{P_J G_J}{B_J}\right)_{min} = \frac{P_t G_t \tau T_{ot} \sigma}{80\pi T_r R^2} F^2(R,\lambda,h) \quad . \tag{50}$$

D. <u>Standoff Jammer</u>

A *STOJ* usually stands off at some specified range beyond the maximum range of the defensive system; that is, there is a constant radar-to-jammer range. This tactic may be less effective than a self-screening or accompanying jammer. For the analysis of a *STOJ* the radar antenna gain parameter is usually subdivided into two parts to account for the possibility of the jammer's being in the main lobe of the radar and conversely, for the jammer's being in the side lobe of the radar.

By modifying Eq. (47) to reflect this fact, the range degradation due to a *STOJ* may be determined from

$$\frac{R_S^4}{R_J^2} \doteq \frac{2.3 \times 10^{-8} P_{tr} G_{tr} \sigma}{P_J G_J \left(\frac{B_r}{B_J}\right)(S/J)} \frac{G_{rt}}{G_{rJ}} \quad , \tag{51}$$

where

G_{rt} = gain of the radar receiving antenna in the direction of the target

G_{rJ} = gain of the radar receiving antenna in the direction of the jammer.

Note from Eq. (51) that if the jammer energy is not being received by the radar side lobes, then the received jamming effectiveness is increased by the ratio of the main lobe gain to the side lobe gain. (The radar antenna target gain and main lobe gain are assumed to be one and the same.) However, the *STOJ* is usually evaluated as being a side lobe jammer. Thus if the side lobes were 20 dB down from the main lobe then the screening range would be increased by a factor of $(100)^{1/4}$ or about 3.2 as compared to a *STOJ* screening range in the main lobe.

E. Trailing Jammer

A jammer that follows the attack aircraft at some preestablished trailing distance, R_t, is classed as a trailing jammer. Such a jamming tactic usually represents a compromise between the self-screening jammer and the *STOJ* from both the standpoint of deliverable power and physical vulnerability.

The screening range for a trailing jammer is readily found to be

$$\frac{R_S^4}{(R_S + R_t)^2} = \frac{2.3 \times 10^{-8} P_{tr} G_{tr} \sigma}{P_J G_J \left(\frac{B_r}{B_J}\right) (S/J)} \quad . \tag{52}$$

It should be noted that the methodologies briefly outlined in this section, although sufficient for most comparative analyses, are restricted for fine-grain analyses. For fine-grain analyses the implicit assumptions must be thoroughly investigated before using any of the models set forth. For example, if the radar under consideration is a track radar, not a search radar, the determination of the effectiveness of the system is complicated by such system considerations as the range at which the tracking errors become intolerable to the system solution.

Furthermore, consideration should be given to radars with burnthrough capability. Reference 34 defines burnthrough as increasing the signal energy $(P_t G_{tr} \tau)$ for purpose of overpowering jammer noise. Thus the energy gain product in the initial analysis will differ from the energy gain product once the radar has been assumed to be jammed.

Likewise such system considerations as assuming that the radar receiver perfectly rejects image jamming may not be valid in the pragmatic case. However, the rejection of such investigations is minimal for most comparative analyses, especially in the preliminary phases. Such a procedure was adhered to in this section.

F. Summary

This section has presented some of the methodologies that are used in evaluating the range degradation of a radar system in a non-benign environment. Due to time and space constraints only the effects of noise jammers were considered, with the acceptance of the rationale that the defensive radars will employ an ECCM strategy that will force the jammer to optimize his tactics around such jamming techniques. Only the basic missions of noise jammers were considered, though the omission of such tactics as the employment of chicks does not necessarily mean that their role is minor.

Since the self-screening jammer and the standoff jammer represent an upper and lower bound on the jamming tactic, a useful tactic for an analysis is the trailing jammer. The effect of chaff on a system is similar to that of rain, and as such the same methodology is usually used to evaluate the expected degradation of the radar system in the presence of either.

In an analysis of a system that is under barrage jamming, considerations must be given to the possibility that the system may have a burn-through mode, that is, that its energy gain product may vary as a function of the severity of the environment. Furthermore, due credence should be given to systems that employ a frequency diversity capability although the analysis should usually remain insensitive to systems that might have a frequency agility capability.

The classified section of this research memorandum* may be consulted for the evaluation of the various ECCM fixes that might be incorporated into a system that will attempt to force a jammer to optimize his tactic around barrage jamming.

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*To be published soon.

Two useful graphs in the analysis of a radar system in a non-benign environment are shown in Figs. 8 and 9.

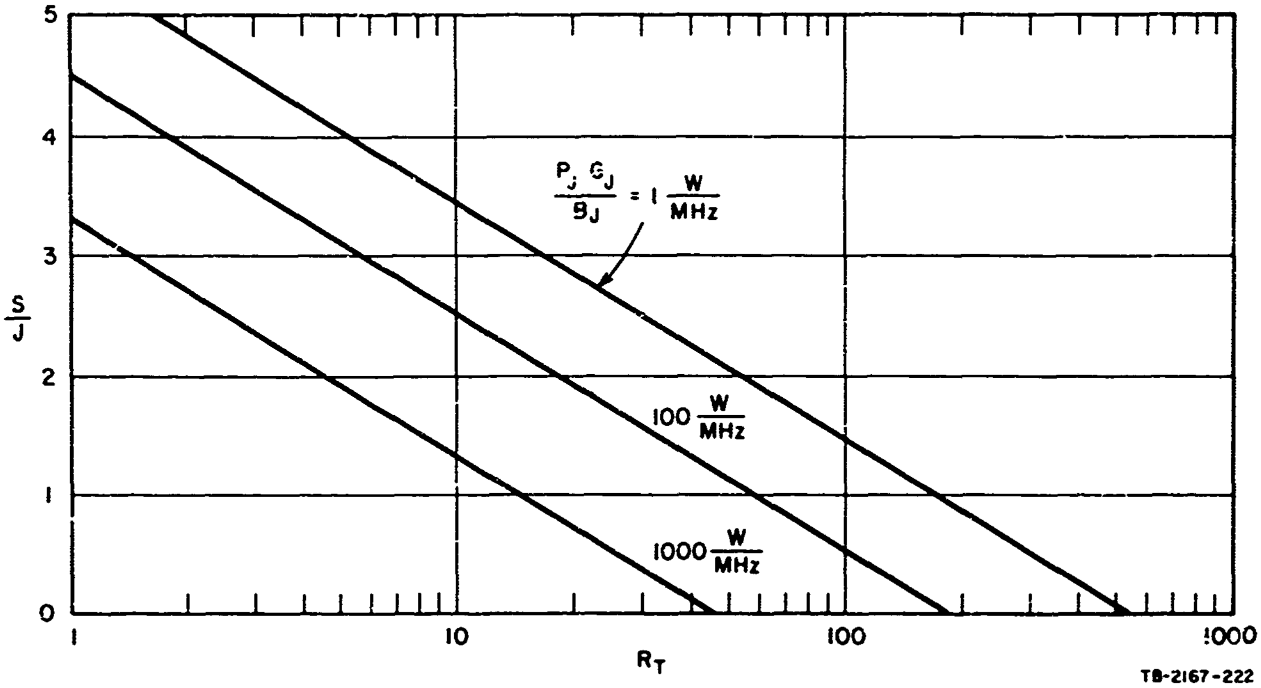


FIG. 8 R_t AS A FUNCTION OF S/J FOR A STOJ

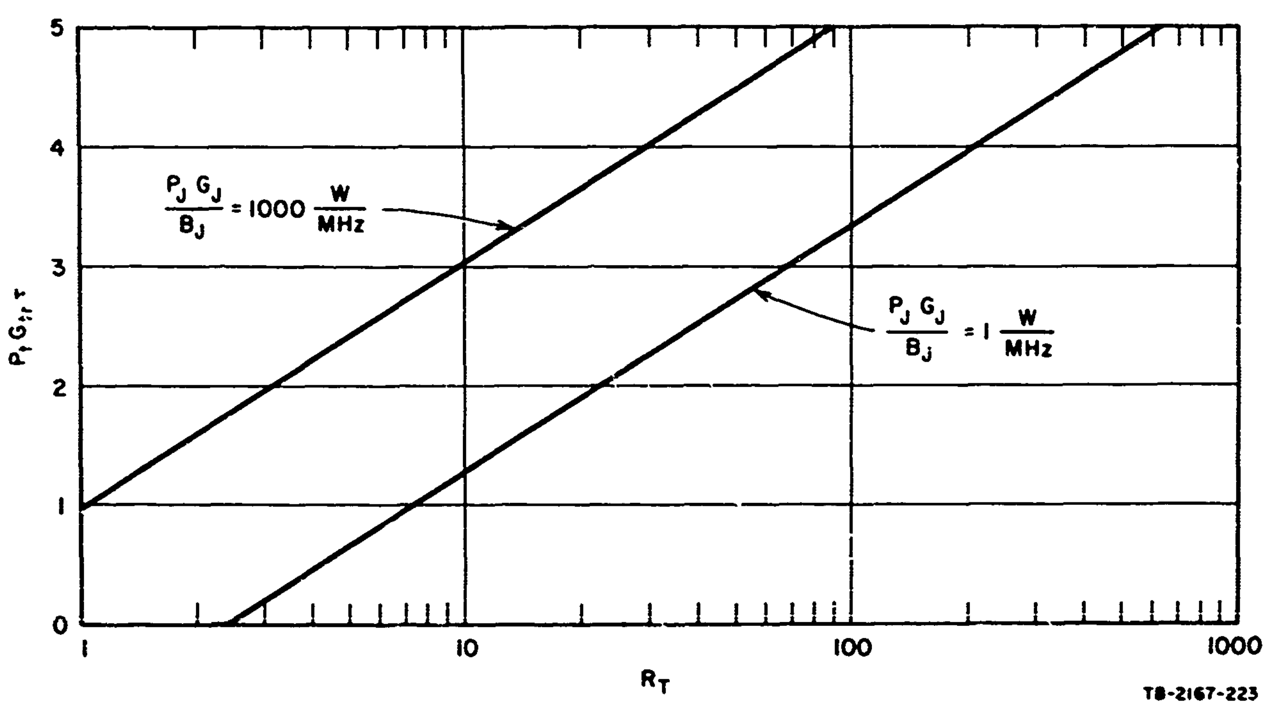


FIG. 9 R_t AS A FUNCTION OF EGP FOR A STOJ

IV VOLUME CLUTTER FOR A CW RADAR

A. General

In a CW radar, the majority of clutter returns within the beam will contribute to an integrated clutter echo. However, the predominate contributors to the integrated clutter echo arise from those volume scatterers that are located at a relatively close range. Therefore the lower bound on the integration of the total integrated clutter echo is at the transition region between the Fresnel and Fraunhofer regions of the antenna pattern. Consequently Eq. (33) will be weighted by two additional terms to account for the changes in the area of the clutter disc with range.

B. Clutter Cross-Section Derivation

Assuming an incremental disc of clutter located at some range, R_c, then from Eq. (33) the volume of this clutter element is

$$dV_c = \frac{\pi}{4}\theta_a\theta_e R_c^2 dR \quad (53)$$

where the range resolution has been written in incremental symbology.

Weighting Eq. (53) by an $(R_c/R)^4$ factor and by an $(R/R_c)^2$ term, the incremental volume of clutter may be written as

$$dV_c = \frac{\pi}{4}\theta_a\theta_e R_c^2 \left(\frac{R_c}{R}\right)^4 \left(\frac{R}{R_c}\right)^2 dR \quad . \quad (54)$$

Integrating this volume of clutter from some minimum value of R, (R_m), to infinity, it is easily seen that the volume of clutter is simply

$$V_c = \frac{\pi}{4}\theta_a\theta_e R_c^4 \frac{1}{R_m} \quad . \quad (55)$$

As was stated in Section II-B,

$$R_{*} = \frac{D^2}{\lambda} \quad . \tag{56}$$

Therefore the total volume clutter for a CW radar is simply

$$V_c = \frac{\pi}{4} \theta_a \theta_e R_c^4 \frac{\lambda}{D^2} \tag{57}$$

where D is the aperture width, and the S/C ratio for volume clutter for a CW radar is

$$\frac{S}{C} = \frac{\sigma_t}{\frac{\pi}{4} \theta_a \theta_e R_c^4 \frac{\lambda}{D^2} \eta} \quad . \tag{58}$$

Equation (58) may be used to determine the minimum required SCV (to be discussed in Section V) for the CW radar in rain or chaff environments. Also the model presented may be used in evaluating the expected degradation of a CW search radar or track radar in the presence of varying rain or chaff densities.

V CLUTTER SUPPRESSION METHODOLOGY

A. General

The signal-to-clutter ratios derived in the previous sections are valid in an analysis that is insensitive to the processing techniques of the radar receiver. However, in many instances, the radars under evaluation will employ some form of clutter suppression.

The techniques for achieving clutter suppression are usually subdivided into four categories: spatial selectivity, time selectivity, signal selectivity, and frequency selectivity. An example of each is, in the same order, side lobe blanking, moving target indicator (*MTI*), pulse width discrimination, and velocity tracking. Since only representative values of clutter suppression are needed for most comparative analysis, only a representative clutter suppression technique will be discussed: in particular, a time selectivity technique-*MTI*.

The model for a double delay line canceller is developed in this section. The mechanism used to make the model sensitive to the various forms of clutter that may be encountered is Barlow's number. A double delay line canceller was selected as the basic model since it appears to represent the optimum technique from a cost and performance viewpoint. Naturally it is realized that no single technique is sufficient for all forms of clutter, and video cancellers are in some instances better than *IF* cancellers. However, the discussion will be limited to *IF* cancellers only, and the values obtained are representative values that may be used to improve the *S/C* ratios calculated from the models in the previous sections.

There are three common terms that are used to express the effectiveness of *MTI* operation: *SCV*, cancellation ratio, and Bernard Steinberg's improvement factor. Reference 35 defines *SCV* as that ratio, in decibels, of the strength of the echo produced by a signal generator of random phase that is barely detectable on a plan position indicator (*PPI*) in clutter with which it coincides in range during normal system operation, to the strength of the echo barely detectable when the *MTI* is in operation and the adjustments are such that the clutter itself is not visible.

Reference 36 defines *SCV* as the ratio of peak moving target signal to peak fixed target signal existing at the input when the two signals are equal in amplitude at the output. As is stated in Ref. 14, there is no Institute of Radio Engineers (*IRE*) definition of this term, and the property of an *MTI* radar which can best be defined and measured is its cancellation ratio. The *IRE* definition of this term is: "In a radar *MTI* system, the ratio of a fixed target signal voltage after cancellation to the voltage of the same target without *MTI* cancellation."

Reference 1 defines the Steinberg improvement factor, (hereafter simply referred to as the improvement factor I) as the target to clutter power ratio at the output of the *MTI* filter divided by the target to clutter ratio at the receiver input. The interrelationships between these factors will be discussed throughout this section.

Since the actual modeling methodology is to calculate the clutter attenuation (*CA*) of the *MTI* filter, it will be assumed that this value is the same as the *SCV* ratio. Reference 31 defines the *CA* factor as the ratio of the input power divided by the output power. Thus if a calculation shows that the clutter attenuation, of rain, for example, results in 30 dB cancellation, then it is assumed that the radar has an *SCV* of 30 dB for rain. In the following discussion the basic terminology is introduced in the derivation of the clutter attenuation for a single delay line canceller and the clutter attenuation for a double delay line canceller is then described. Barlow's parameters are tabulated to facilitate modeling under various forms of clutter.

B. Single Delay Line Cancellers

Adhering to the procedure outline in Ref. 37, the attenuation of the clutter signal due to *MTI* cancellation is defined as

$$CA = \frac{\int_0^\infty |g_1(f)|^2 df}{\int_0^\infty |g_2(f)|^2 df} = \frac{\int_0^\infty |g_1(f)|^2 df}{4\int_0^\infty |g_1(f)|^2 \sin^2\left(\pi \frac{f}{f_r}\right) df} \tag{59}$$

where the limits of integration are from zero to the reciprocal of the pulse repetition frequency (*PRF*), $g_1(f)$ is the Fourier transform of the input and f_r is the *PRF*. From Ref. 38,

$$|g_1(f)|^2 = |g_1(0)|^2 \exp - a\left(\frac{f}{f_o}\right)^2 \tag{60}$$

where

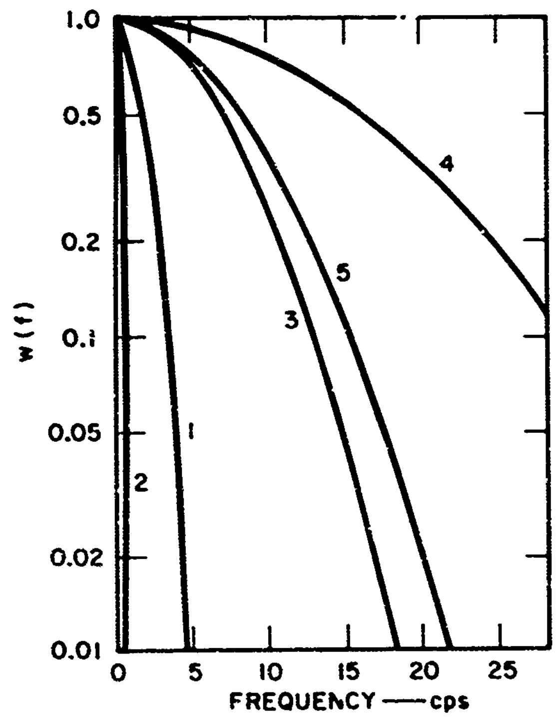
$g(f)$ = clutter power spectrum as a function of frequency

f_o = radar transmitter frequency

a = a parameter dependent upon clutter (Barlow's number).

Figure 10, taken from Ref. 38, is a plot of Eq. (60) for various clutter sources. Substituting Eq. (60) into Eq. (59),

$$CA = \frac{\int_0^\infty \exp -a\left(\frac{f}{f_o}\right)^2 df}{4\int_0^\infty \sin^2\left(\pi \frac{f}{f_r}\right) \exp -a\left(\frac{f}{f_o}\right)^2 df} \quad . \tag{61}$$



SOURCE: Ref. 38. TA-2167-224

FIG. 10 POWER SPECTRA OF VARIOUS CLUTTER TARGETS (1) Heavily wooded hills, 20-mph wind blowing ($a = 2.3 \times 10^{17}$); (2) Sparsely wooded hills, calm day ($a = 3.9 \times 10^{19}$); (3) Sea echo, windy day ($a = 1.41 \times 10^{16}$); (4) Rain clouds ($a = 2.8 \times 10^{15}$); (5) Chaff ($a = 1 \times 10^{16}$).

Then integrating, the clutter attenuation factor for a single delay line canceller (signal gain of 4; for a double delay line canceller signal gain is 16, and for a triple delay line canceller the signal gain is 64) may be written as

$$CA = \frac{1}{2\left[1 - \exp - \left(\pi \frac{f_o}{f_r}\right)^2 \frac{1}{a}\right]} \quad . \tag{62}$$

Since the frequencies usually involved are far in excess of the *PRF* frequencies, Eq. (62) may be written, with little loss in accuracy as

$$CA \doteq \frac{a}{2\left(\pi \frac{f_o}{f_r}\right)^2} \quad . \tag{63}$$

From Ref. 1, the improvement factor for a single delay line canceller is

$$I = \frac{1}{2}\left(\frac{f_r}{\pi\sigma_c}\right)^2 \tag{64}$$

where σ_c is the standard deviation of the lobes of the clutter spectrum in the intermediate frequency. Exact expressions for the improvement factor for both coherent and noncoherent integration are listed as

$$I_c^{-1} = 1 - e^{-2\pi^2\sigma_c^2(1/f_r)^2} \quad . \tag{65}$$

$$I_N^{-1} = \frac{1}{2} \; 1 - e^{-4\pi^2\sigma_c^2(1/f_r)^2} \quad . \tag{66}$$

σ_c may be related to Barlow's number by

$$\sigma_- = \frac{2\sigma_v}{\lambda} = \frac{2c}{\lambda\sqrt{8a}} \tag{67}$$

where σ_v is the rms velocity spread of the scattering elements and c is the velocity of propagation.

Table III, from Ref. 14, lists some characteristics of clutter spectra.

Table III

CHARACTERISTICS OF CLUTTER SPECTRA

SOURCE OF CLUTTER	WIND SPEED (knots)	RATIO m^2	BARLOW'S a	$\sigma c \lambda$ (cm/sec)	σv (ft/sec)
Sparse woods	(calm)		3.9×10^{19}	3.5	0.057
Rocky terrain	10	30			
Wooded hills	10	5.2	7.2×10^{18}	8	0.13
Wooded hills	20		2.3×10^{17}	45	0.74
Wooded hills	25	0.8	9×10^{17}	23	0.38
Wooded hills	40	0	1.1×10^{17}	65	1.06
Sea echo			2.4×10^{16}	140	2.3
Sea echo		0	$(1 - 2) \times 10^{16}$	165 - 205	2.5 - 3.3
Sea echo	8 - 20		$(0.6 - 2.6) \times 10^{16}$	100 - 220	1.5 - 3.5
Sea echo	(windy)		1.4×10^{16}	183	3.0
Chaff	0 - 10	0	$(1.4 - 8) \times 10^{16}$	75 - 180	1.2 - 3.0
Chaff	25	0	7×10^{15}	250	[illegible].1
Chaff			10^{16}	215	3.5
Rain clouds		0	$(0.7 - 3) \times 10^{15}$	370 - 800	6 - 13
Rain clouds			2.8×10^{15}	410	6.7

SOURCE: Ref. 14.

C. Double Delay Line Cancellers

Following the same procedure as outlined above in Section B, the clutter attenuation for a double delay line canceller is, from Ref. 31,

$$CA = \frac{0.5}{3 - 4 \exp\left[-\left(\pi \frac{f_o}{f_r}\right)^2 / a\right] + \exp\left[-4\left(\pi \frac{f_o}{f_r}\right)^2 / a\right]} . \qquad (68)$$

For most radar cases, this expression may be approximated, with little loss in accuracy by

$$CA \doteq \frac{a^2}{12\left(\pi \frac{f_o}{f_r}\right)^4} \qquad (69)$$

From Ref. 1, the improvement factor for a double delay line canceller may be written as

$$I_c = \left[1 - \frac{4}{3} e^{-2\pi^2 \sigma_c^2 \frac{1}{f_r^2}} + \frac{1}{3} e^{-8\pi^2 \sigma_c^2 \frac{1}{f_r^2}}\right]^{-1} \doteq \frac{1}{8}\left(\frac{f_r}{\pi f_c}\right)^4 \qquad (70)$$

and

$$I_S = 2\left[1 - \frac{4}{3} e^{-4\pi^2 \sigma_c^2 \frac{1}{f_r^2}} + \frac{1}{3} e^{-16\pi^2 \sigma_c^2 \frac{1}{f_r^2}}\right]^{-1} \doteq \frac{1}{16}\left(\frac{f_r}{\sigma_c}\right)^4 \quad . \qquad (71)$$

D. Barlow's Parameter

The model for a double delay canceller requires a value for Barlow's parameter. This parameter is dependent on the type of clutter under consideration. Table III listed some typical values for Barlow's number. Figure 11, taken from Ref. 37, graphically depicts the variation of Barlow's

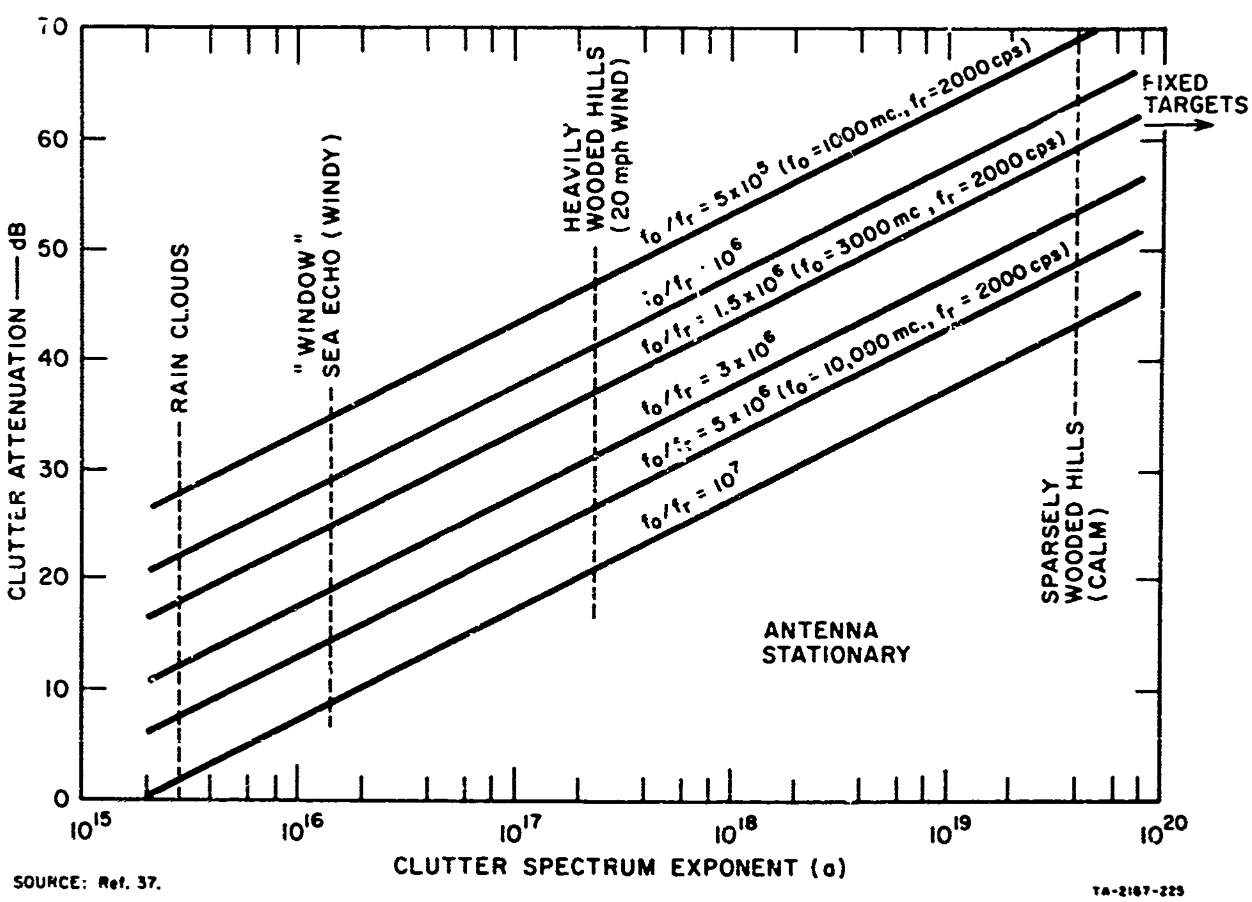
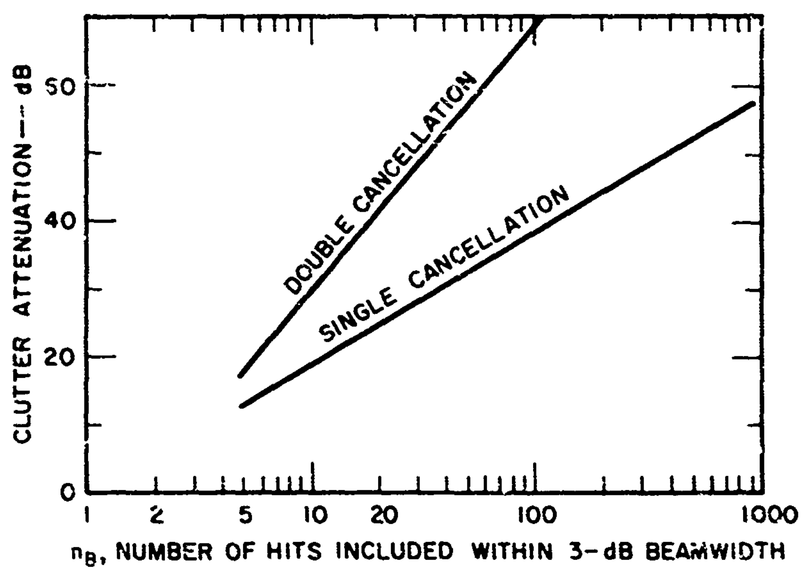


FIG. 11 EFFECT OF INTERNAL FLUCTUATIONS ON CLUTTER ATTENUATION

number with various types of clutter. The values of CA obtained from the above mentioned methodology should be increased by about 10 dB to account for such realistic degradations in system performance as frequency and timing degradations. Thus a computed SCV of 45 dB would realistically represent a SCV of about 35 dB. Fluctuations due to scanning limit one source of clutter to a double delay line canceller. Figure 12, taken from Ref. 31, gives representative values of the attenuation of these fluctuations. Thus a system may have an SCV for ground clutter fluctuations on the order of 90 dB (CA) but the scanning loss may r more dominant at about 45 dB. Then an SCV of about 35 dB should be used for the evaluation of the S/C ratio for ground clutter.



SOURCE: Ref. 31.

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FIG. 12 CLUTTER ATTENUATION WITH A SCANNING ANTENNA FOR SINGLE CANCELLATION AND DOUBLE CANCELLATION

The methodologies set forth in this section afford the analyst representative values of clutter suppression techniques for comparative analysis purposes. The equations also illustrate the concepts and system considerations that must be identified during a performance evaluation analysis.

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13 ABSTRACT

This report describes the major system methodologies pertinent to the evaluation of contemporary fire control systems. It will serve as a useful reference for the systems analyst and as an aid for those who want to supplement their knowledge of the methodologies associated with radar systems analysis. Major emphasis is given to the description of radar performance in a benign and a nonbenign environment. Extensive references are included. This work was undertaken as part of a larger study of radar performance evaluation for the Naval Warfare Research Center of Stanford Research Institute.

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